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Paradoxical lightness contrast

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ABSTRACT

The visual system's computation of lightness (perceived reflectance) leads to contrast effects in which a gray target region appears lighter on a black background than on a white one. Here we show a paradoxical contrast effect in which targets look *lighter* after adding regions that increase the scene's average luminance, and *darker* after adding regions that decrease this luminance. The paradoxical effect emerges if the target sits either on a black local background surrounded by a white remote background, or on a white local background surrounded by a black remote background. It does not occur if both backgrounds have the same luminance. The effect is consistent with Bressan's double-anchoring theory, and likely also with those edge-integration theories that assume gain control, but differs from previously reported effects of assimilation, articulation, reverse contrast, and remote contrast.

1. Introduction

An illuminated region reflects a certain proportion of the incident light, and this proportion (*reflectance*) is informative about the region's identity. Unfortunately, the eye has access only to a region's *luminance* (total amount of light reflected or emitted) and cannot possibly acquire direct information about reflectance. If a black and a white region are illuminated equally, then their luminances are good indicators of their reflectances. A strongly illuminated black region, however, can have a higher luminance than a poorly illuminated white region. In this case, luminances are not good indicators of reflectances, and the visual system has to somehow discount the difference in illumination. To generate a percept of the reflectance of a particular region (its shade of gray or *lightness*), the visual system uses the ratios between the luminance of the target and the luminances of the surrounding regions. Under natural conditions, these luminance ratios are less affected by illumination than the luminances themselves, but their use leads to a side effect whereby identical targets are seen as darker on a high-luminance background, and lighter on a low-luminance background (*simultaneous lightness contrast effect*).

In the current article, we show how double-anchoring theory (Bressan, 2006a), and most likely also those edge-integration theories that assume gain control (e.g., Rudd & Arrington, 2001; Vladusich, Lucassen, & Cornelissen, 2006), suggest the existence of a hitherto unreported paradoxical lightness contrast effect. This effect has a direction opposite to that of contrast, but we will show in the discussion that it differs from both so-called "reverse contrast" and various other superficially similar effects. In the paradoxical contrast effect, adding high-luminance regions to the scene has the net effect of lightening targets, rather than darkening them, and adding low-luminance regions has the net effect of darkening targets, rather than lightening them. Critically, though, the effect occurs if, and only if, the local background is surrounded by a remote background, and one of these two backgrounds is more, and the other less, luminant than the targets.

According to the double-anchoring theory of lightness (Bressan, 2006a, 2006b, 2007), which is a development of the anchoring theory of Gilchrist et al. (1999), different surrounding regions can be differently informative about a target region's reflectance. Bressan hypothesized that the visual system assigns a relative weight to each luminance ratio between a target and a surrounding region, and that this weight is proportional to the strength of the perceptual grouping between the two regions. Grouping principles, in this context, are the photometric constraints (e.g., luminance polarity; see Section 3) and spatial constraints (e.g., proximity) that are likely to be shared by regions that are similarly illuminated, whereby the principles that represent a better proxy for common illumination receive more weight. The nature, and relative importance, of the specific grouping principles (Bressan, 2006a, 2007) are irrelevant for our present purpose. Just the hypothesis that the visual system does indeed assign relative weights to different luminance ratios is sufficient to predict the occurrence of the paradoxical lightness effect.

Consider the stimuli depicted in the insets A–D of Fig. 1 (shown not simultaneously, but one at a time). Eight target disks are presented (light gray in insets A and B, and very dark gray in insets C and D), either along with 56 contextual disks (respectively, mid

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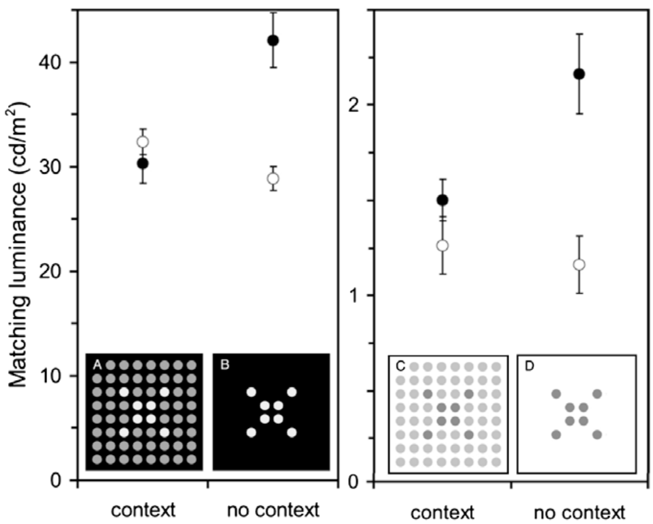

Fig. 1. Insets A–D show illustrations of the stimuli (for clarity sake, exact gray shades deviate somewhat from those used in the experiments); these were surrounded by either a black or a white remote background (not shown). The stimuli either contained contextual disks (insets A and C) or did not (insets B and D). The observers matched the luminance of an adjustable disk until its lightness corresponded to that of the targets, and these luminance matches are shown on the ordinate. Closed symbols show the results obtained with a black remote background (Experiment 1), and open symbols those obtained with a white remote background (Experiment 2). Note that the ordinates of A and B and of C and D differ in scale. Error bars represent one standard error of the mean.

gray and dark gray in insets A and C) or without them (insets B and D). The targets and, if present, the contextual disks, are placed on a local background (black in insets A and B, white in insets C and D). This local background, in turn, is placed on a larger background (the remote background) that is either black or white. The contrast between the luminance of the target disks and the average luminance around them is larger in inset B than in inset A, and also larger in inset D than in inset C. Hence, a contrast effect should cause targets to appear lighter in inset B than in inset A, and darker in inset D than in inset C.

In our experiments, we hold the local backgrounds constant and manipulate the remote ones. Of particular interest is the situation in which the local background is black and the remote background white (insets A and B on a white remote background), or vice versa (insets C and D on a black remote background). By definition, the sum of relative weights assigned to luminance ratios is constant (Bressan, 2006a). Hence, the weights assigned to the luminance ratios between the targets and other regions should be larger when the contextual disks are absent than when they are present. If the local background is sufficiently small, and the remote background sufficiently large, such that the effect of the latter is stronger than the effect of the former, then a paradoxical lightness contrast should occur. In case of insets A and B, the white remote background should darken the targets less in the presence of the contextual disks than in their absence; in the case of insets C and D, the black remote background should lighten the targets less in the presence of the contextual disks than in their absence.

In other words, in the case of insets A and B with a white remote background, adding contextual disks that increase the average luminance around the targets should lighten, rather than darken, the targets: an effect opposite to that of lightness contrast. In the case of insets C and D with a black remote background, adding contextual disks that decrease the average luminance around the targets should darken, rather than lighten, the targets: again an effect opposite to that of lightness contrast.

The laboratory in which we conduct our experiments is always dark. If the remote background is white, then the laboratory itself constitutes a second remote background with an effect opposite to that of the regular remote background on the computer screen. The effect of the regular remote background should therefore be smaller if this background is white than if it is black. It is not an option, though, to use a white and well-lit laboratory in the conditions with a white remote background, as the illumination would be reflected by the computer screen and reduce the displayed contrasts. The large region of white around the screen would also introduce glare in the eyes. In fact, even in a dark laboratory, some glare is predictable if the stimulus contains large white regions. Effects should therefore be expected to be weaker when the remote background is white than when it is black.

2. Experiments

2.1. Methods

2.1.1. Subject

Fifty-nine undergraduates at the University of Padova, with normal or corrected-to-normal vision, volunteered to participate (26 in Experiment 1, in which the remote background was black, and 33 in Experiment 2, in which the remote background was white).

2.1.2. Apparatus

Stimuli were shown on a calibrated BARCO monitor (1280×960 pixels), using Prolog on a Macintosh G4 computer. The laboratory was dark and the border around the screen was covered with black cardboard. Thus, when the local and remote backgrounds were both black, the targets had the highest luminance of any region in the entire laboratory. Viewing distance, controlled with a chin-and-head rest, was 60 cm.

2.1.3. Stimuli and procedure

The four stimuli used in the current experiments were randomly intermixed with other ones, irrelevant for the present purpose and discussed in Bressan and Kramer (2008). In the stimuli illustrated in Fig. 1, left panel, insets A and B, the targets were light gray (39.96 cd/m^2), the contextual disks mid gray (14.50 cd/m^2), the local background black (0.07 cd/m^2), and the remote background either white (82.88 cd/m^2) or black. In the stimuli illustrated in Fig. 1, right panel, insets C and D, the targets were very dark gray (1.45 cd/m^2), the contextual disks dark gray (5.70 cd/m^2), the local background white, and the remote background either white or black. Target and contextual disk diameters were 1 cm, and the local background was 11×11 cm. An adjustable disk (diameter 1 cm, initial luminance randomly chosen between 3.54 and 6.55 cd/m^2) was displayed at the bottom of the screen, centered on a horizontal strip (2×45 cm) that had the same luminance as the local background of the target. (Target and matching disks, thus, always had the same luminance polarity, which renders the task easier; e.g., Vladusich, Lucassen, & Cornelissen, 2007; Whittle, 1994.) Observers reduced or increased the adjustable disk's luminance, until its lightness matched that of the targets, by clicking on a left or right button in the lower-right corner of the screen.

2.2. Results

We performed two separate ANOVAs for the two data sets shown in the left and right panels of Fig. 1 (with one missing value in the second data set due to a technical malfunction). In both data sets, remote-background luminance affected target lightness more in the absence, than in the presence, of the contextual disks (respectively, $F(1,57) = 26.55$, $p < .001$, and $F(1,56) = 9.65$, $p = .003$). When the contextual disks were present (insets A and C), the subjects saw little difference in target lightness regardless of whether the remote background was black or white (respectively, closed and open symbols). Instead, when the contextual disks were absent (insets B and D), the targets were perceived as lighter when the remote background was black (closed symbols), and as darker when the remote background was white (open symbols).

Remarkably, when the local background was black and the remote background white (left panel, open symbols), targets were perceived as lighter in the presence, than in the absence, of contextual disks (paired-samples $t(24) = 3.24$, $p = .003$): an entirely new and paradoxical contrast effect. Similarly, when the local background was white and the remote background black (right panel, closed symbols), targets were perceived as darker in the presence, than in the absence, of contextual disks (paired-samples $t(32) = 2.88$, $p = .007$): again a paradoxical contrast effect.

When remote and local backgrounds had the same luminance, the paradoxical effect did not appear. When the local and remote backgrounds were both black, targets were perceived as lighter in the absence, than in the presence, of contextual disks (left panel, closed symbols; paired-samples $t(25) = 3.97$, $p = .001$), which is consistent with a simultaneous contrast effect (for a discussion of the theoretical importance of such a simultaneous contrast effect in which the targets have the highest luminance in the scene, see Bressan & Actis-Grosso, 2006). When the local and remote backgrounds were both white, the mean matching luminance was higher in the presence, than in the absence, of contextual disks, though the effect did not reach significance (right panel, open symbols; paired-samples $t < 1$).

To be complete, we also report the main effects of our two ANOVAs here. We found main effects of the remote background (tested between subjects) and of the contextual disks (tested within subjects). In the first data set (left panel), we found mean matching luminances of 30.58 cd/m^2 when the remote background luminance was high (the average of the open-symbol data) and of 36.18 cd/m^2 when it was low (the average of the closed-symbol data), $F(1,57) = 8.31$, $p = .006$: a regular contrast effect. We found mean matching luminances of 31.43 cd/m^2 when the contextual disks were present (the average of the data shown in inset A) and of 34.67 cd/m^2 when they were absent (the average of the data shown in inset B), $F(1,57) = 7.85$, $p = .007$: again a regular contrast effect.

In the second data set (right panel), we found mean matching luminances of 1.21 cd/m^2 when the remote background luminance was high (the average of the open-symbol data) and of 1.84 cd/m^2 when it was low (the average across the closed-symbol data), $F(1,56) = 9.72$, $p = .003$: a regular contrast effect. We found mean matching luminances of 1.36 cd/m^2 when the contextual disks were present (the average across the data shown in inset C) and of 1.60 cd/m^2 when they were absent (the average across the data shown in inset D), $F(1,56) = 9.72$, $p = .003$: an effect opposite to lightness contrast. Fig. 1, right panel, shows that the condition with the black remote background drives this effect, as also suggested by the interaction reported earlier in this results section.

As predicted, Fig. 1 shows that both the contrast and paradoxical contrast effects were stronger when the remote background was black and encompassing the entire laboratory (closed symbols) than when the remote background was white and confined to the size of the computer screen (open symbols).

3. Discussion

We found a paradoxical lightness effect in which targets appeared lighter with, than without, the addition of high-luminance regions onto the scene, and appeared darker with, than without, the addition of low-luminance regions onto the scene. The effect occurred when the local background was itself surrounded by a remote background, and one of the backgrounds was more, and the other less, luminant than the targets. It did not occur when the two backgrounds had the same luminance.

Although the paradoxical contrast effect is opposite to the effect of contrast, it is different from "reverse contrast" effects, such as Benary's cross (1924), White's effect (1979), De Valois and De Valois's checkerboard illusion (1988), Agostini and Galmonte's Necker-cube effect (2002), or Bressan's dungeon illusion (Bressan, 2001; Bressan & Kramer, 2008).

The stimuli that give rise to the dungeon illusion are very similar to the ones used here. In those stimuli, however, the luminance of the targets is always in between the luminances of the contextual disks and of the local background, whereas in our current stimuli, it is either higher (Fig. 1A), or lower (Fig. 1B), than the luminances of both the contextual disks and the local background. Thus, the contrast between the targets and the local background, and the contrast between the targets and the contextual disks, go in opposite directions in the dungeon illusion and in the same direction in the paradoxical effect. The two phenomena, as a result, are also quite different. Both types of stimuli give rise to a lightness effect between the targets and their local background that is opposite to contrast. Between the targets and the contextual disks, however, the dungeon illusion gives rise to a regular contrast effect, whereas our current stimuli again lead to an effect opposite to contrast. That is, in the dungeon illusion, the targets are *darkened* by contextual disks with a higher, and *lightened* by contextual disks with a lower, luminance than that of the local background. In the paradoxical contrast effect, instead, the targets are *lightened* by contextual disks with a higher, and *darkened* by contextual disks with a lower, luminance than that of the local background.

Compare, respectively, the open symbol in Fig. 1A to the one in Fig. 1B, and the closed symbol in Fig. 1C to the one in Fig. 1D. Note that the two open-symbol data points in Fig. 1A and B, that reveal the paradoxical effect, were both obtained with the same local and remote backgrounds. Hence, neither the local, nor the remote, background per se could have been responsible for this effect. A similar argument holds for Fig. 1C and D. Thus, whereas reverse-contrast effects can be due to the dominance of one regular contrast effect over another, the paradoxical effect cannot. In the dungeon illusion, for example, the reverse contrast could be due to the dominance of the regular contrast between the targets and the contextual disks over the regular contrast between the targets and their surround, that goes in the opposite direction. In the paradoxical effect, however, neither a dominance of the contrast between the targets and the contextual disks, nor a dominance of the contrast between the targets and the remote background, could drive the lightness effect between the targets and their surrounding regions in the direction opposite to contrast. The paradoxical effect thus confirms our hypothesis that a lightness effect can be due to a shift in the weight distribution of contrasts rather than to any of those contrasts per se.

Although paradoxical contrast differs from reverse contrast, both go in a direction opposite to contrast, and in this sense they are similar. Likewise, paradoxical contrast is also, to some extent, similar to *assimilation* and *articulation*. In *assimilation*, a target becomes perceptually more similar to its surround (Whittle, 1994). Due to the presence of the contextual disks, the surround of the targets has a higher average luminance in Fig. 1A than in Fig. 1B. The paradoxical effect that emerges when the remote background is white (open symbols) therefore resembles an effect of assimilation. The paradoxical contrast effect, however, is replaced by a regular contrast effect when the remote background is black (closed symbols), and this dependency on the remote background is inconsistent with an effect of assimilation. A similar argument holds for Fig. 1C and D.

A regular contrast effect between a target and its local surround increases with the luminance variance (articulation) of the surround itself (e.g., Bressan & Actis-Grosso, 2006; Gilchrist & Annan, 2002). Due to the presence of the contextual disks, the surround of the targets is more articulated in Fig. 1A than in Fig. 1B. The surround also has a higher luminance in Fig. 1A than in Fig. 1B, but the effect of articulation might well be stronger than the effect of contrast. If so, then the paradoxical target lightening that occurs when the remote background is white (open symbols) is similar to an effect of articulation. Articulation, however, lightens light targets on dark backgrounds even when the stimuli fill the entire screen and the only remote background is the dark laboratory (Bressan & Actis-Grosso, 2006). When our remote background was black (closed symbols), instead, the target on the articulated surround (Fig. 1A) darkened, rather than lightened, relative to the target on the uniform surround (Fig. 1B).

Paradoxical contrast, finally, should not be confused with the remote contrast effects that emerge in Wolff's (1934), or Reid and Shapley's (1988) displays. The latter, for example, consists of two target squares that have identical luminances, surrounded by square frames that also have identical luminances. The latter frames, in turn, are surrounded by square frames with different luminances. The target square with the more luminant outer frame looks darker than the target square with the less luminant one. This is, however, a simple remote contrast effect due to a difference between the two remote surrounds. Our paradoxical effect, on the contrary, occurs with identical remote surrounds and depends on the addition of contextual elements (which produce an effect that is actually opposite to remote contrast).

Our present goal was to test the hypothesis that the visual system assigns relative weights in lightness computation. We did this by testing the prediction, derived from this hypothesis, that the paradoxical effect should exist. We avoided auxiliary assumptions as much as possible, and for that reason we also avoided introducing perceptual grouping. In Bressan's (2006a) double-anchoring model of lightness, however, different relative weights implement different grouping strengths. Bressan and Kramer (2008), indeed, showed that the effects of remote regions on target lightness depend on grouping, and in particular on grouping by luminance polarity, whereby two regions group well if they are both more, or both less, luminant than the background, and otherwise group poorly (Masin, 2003). In particular, they found that good grouping by luminance polarity between targets and nearby contextual regions eliminated an otherwise clear effect of the remote background on target lightness.

Although our current study is not concerned with grouping, its results are consistent with those of Bressan and Kramer. In Fig. 1B and D, there is a strong effect of the remote background on target lightness (for both figures, compare the open and closed symbols to each other). In Fig. 1A and C, instead, in which there is good grouping by luminance polarity between the targets and the nearby contextual regions, the effect is absent (for both figures, compare the open and closed symbols to each other and notice that, statistically, they overlap). Hence, although our current study is not concerned with grouping, it does support the work by Bressan and Kramer that is concerned with grouping. (For additional evidence for grouping effects in lightness, collected with stimuli typically used in edge-integration studies, see Pereverzeva & Murray, 2009.) An important difference between the current study and the one by Bressan and Kramer (2008) is that the current study, unlike Bressan and Kramer's, allowed a comparison of conditions in which the local and remote backgrounds were both held constant and only the contextual disks were manipulated. It was this comparison that was critical to the demonstration that the paradoxical effect exists.

Although we predicted the existence of the paradoxical contrast effect with the help of double-anchoring theory's idea of weight assignment, it is likely that those edge-integration theories that assume gain control can also explain our results. Edge-integration theories (for a review, see Vladusich et al., 2006; see also Rudd & Popa, 2007; Rudd & Zemach, 2007) argue that dark-to-light edges around a target (with the target being on the dark side of the edge) darken it, and that light-to-dark edges around a target lighten it. The edge effects have weights that are inversely proportional to their distance from the target, and it is often assumed that nearby edges can also partially block the effect of edges further away (*gain control*). A typical edge-integration stimulus is a central target disk surrounded by one or more concentric rings. In our stimuli, the contextual disks may function in a way similar to those concentric rings. The edges of the contextual disks could partially block the effects of the remote background, because they are closer to the targets than the edges of the remote background itself. Thus, also according to edge-integration theories that assume gain control one would expect the remote background to affect the targets more in insets B and D, than in insets A and C, of Fig. 1.

Following these edge-integration theories, the effect of the remote background should be largest when its nearby edge is close to the targets and when its outer edge is either absent, or far away, from these targets (Rudd & Popa, 2007; Vladusich et al., 2006). Like double-anchoring theory, therefore, edge-integration theories predict that the effect of the remote background should decrease with the area of the local background and increase with the area of the remote background.

4. Conclusions

In conclusion, we found a paradoxical lightness contrast effect in which targets look *lighter* after adding regions that increase the scene's average luminance, and *darker* after adding regions that decrease this luminance. The effect is consistent with Bressan's double-anchoring theory, and likely also with those edge-integration theories that assume gain control. In addition, paradoxical contrast is in some respects similar to, but in others critically different from, previously reported effects of assimilation, articulation, remote contrast, and reverse contrast.

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